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6. AUTHOR(S)
Professor John H. Booske

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

UNIVERSITY OF WISCONSIN (LEAD)
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF MICHIGAN – ANN ARBOR
TEXAS TECH UNIVERSITY – LUBBOCK
UNIVERSITY OF CALIFORNIA-BERKELEY

University of Wisconsin
Electrical and Computer Engineering
1415 Engineering Drive
Madison, WI 53706

8. PERFORMING ORGANIZATION

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Dr. Robert Barker
AFOSR/NE
875 North Randoph St,, Suite 325, Room 3-112
Arlington, VA 22203-1768

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The primary objective of this MURI-funded consortium is to enable the realization of long-lived, low-maintenance, and reliable hard-vacuum high power microwave (HPM) device technologies by establishing new physical understanding of electron emission/absorption and plasma breakdown phenomena from the nano- to the macro-scale near conducting and insulating surfaces. The research should generate major advances in cathodes for intense (high power, high current density) electron beams while addressing the problem of electrical breakdown at windows, anodes, and collectors in low and high frequency HPM devices. A second major goal of the consortium is to train outstanding students in the HPM field.

Specific research topics include breakdown and plasma formation within the device and on the air side of vacuum windows, attainment of high current density HPM cathode emission, nonuniform cathode emission, rapid cathode degradation, surface plasma at the cathode, and related topics. All of these challenges arise from working in a regime of extremely high electric field (DC and RF), thermal, and charged particle impact stresses, and must be mitigated to allow reliable operation of HPM devices. The research activities envision application in L/S-band and W-band microwave frequency regimes, consistent with current and anticipated future DoD mission interests.

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ANNUAL TECHNICAL PERFORMANCE REPORT

"THE NANOPHYSICS OF ELECTRON EMISSION AND BREAKDOWN FOR HIGH POWER MICROWAVE SOURCES"

AFOSR GRANT FA9550-04-1-0369

FINAL TECHNICAL REPORT

PARTICIPATING INSTITUTIONS

UNIVERSITY OF CALIFORNIA-BERKELEY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF MICHIGAN – ANN ARBOR
TEXAS TECH UNIVERSITY – LUBBOCK
UNIVERSITY OF WISCONSIN –MADISON **(LEAD)**

PRINCIPAL INVESTIGATOR & POINT OF CONTACT:

PROFESSOR JOHN H. BOOSKE
UNIVERSITY OF WISCONSIN
ELECTRICAL AND COMPUTER ENGINEERING DEPT
1415 ENGINEERING DRIVE
MADISON, WI 53706
BOOSKE@ENGR.WISC.EDU

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1. Objectives

The primary objective of this MURI-funded consortium is to enable the realization of long-lived, low-maintenance, and reliable hard-vacuum high power microwave (HPM) device technologies by establishing new physical understanding of electron emission/absorption and plasma breakdown phenomena from the nano- to the macro-scale near conducting and insulating surfaces. The research should generate major advances in cathodes for intense (high power, high current density) electron beams while addressing the problem of electrical breakdown at windows, anodes, and collectors in low and high frequency HPM devices. A second major goal of the consortium is to train outstanding students in the HPM field.

Specific research topics include breakdown and plasma formation within the device and on the air side of vacuum windows, attainment of high current density HPM cathode emission, nonuniform cathode emission, rapid cathode degradation, surface plasma at the cathode, and related topics. All of these challenges arise from working in a regime of extremely high electric field (DC and RF), thermal, and charged particle impact stresses, and must be mitigated to allow reliable operation of HPM devices. The research activities envision application in L/S-band and W-band microwave frequency regimes, consistent with current and anticipated future DoD mission interests.

2. Progress on Original Statement of Work

The original proposal had 5 main aims, with various sub-aims. Relative to the 5 main aims, we have accomplished virtually all of the original objectives. Below is a brief summary report for each of the original specific aims.

2.1. Determine electron emission mechanisms and identify best candidates for HPM cold cathodes.

UW developed a new cathode research facility, MACX, which enabled basic studies of field emission while varying the temperature of the cathode from 20 – 350 ^{o}C. UM already had a high voltage pulsed power system, MELBA, available to study novel cathodes under HPM conditions. UW developed a Transfer Matrix Method computer model to *independently* extract accurate effective values of work function, field enhancement and emitting area parameters of cathodes. UW and UM collaborated on a study of raised ridge field emitting cathodes, both experimentally and theoretically. UW acquired computational models and expertise in ab initio calculations of work functions for thin film coated cathodes. UCB developed a working definition of effective (cathode-averaged) field enhancement parameter, models for the transition of field to space charge limited emission, and models for secondary electron emission. Applying these experimental and modeling tools, research established that experimentally reported anomalously large field enhancement factors (exceeding 100) are sometimes, and probably most of the time, an artifact of assuming an excessively high work function. Work functions are hard to measure independently of field enhancement factors, but they can be significantly lower than expected due to surface adsorbates. Meanwhile we have proven Schottky's conjecture regarding multiplication of field enhancement factors for microprotrusions on top of macro-protrusions as the probable explanation of higher-than-expected geometric field enhancements for raised ridge cathodes. Working in collaboration with AFRL-Kirtland, we have explained observations of very low turn-on electric fields for CsI-coated graphite fiber cathodes as due to surface electric dipole induced work function reductions. We developed a new theory for electron multiplication at triple points and established an optimal triple point geometry. Novel triple point cathodes, cathode priming in relativistic magnetrons and effects of particulates upon electron emission were experimentally demonstrated and studied.

2.2. Determine prospects for thermionic cathodes for HPM devices

UCB developed/acquired theoretical and simulation models for nonuniform emission related to localized space charge limits and 2D effects. UM (in collaboration with NRL) and MIT separately developed models explaining nonuniform emission in HPM gyrotron cathodes. UW applied ab initio modeling to understanding the issue of low work function and circumstantially high emission efficiency of scandate thermonic cathodes. The UM and MIT gyrotron cathode modeling efforts identified one or more types of mechanical surface finish imperfections as a probable culprit in nonuniform gyrotron cathode emission. MIT developed a new cathode fabrication process protocol to alleviate one of the candidate causes of nonuniform emission and purchased two cathodes. MIT and CCR partnered to develop a new cathode emission measurement method and system. As a result of these modeling and experimental capabilities,

we established that solving the gyrotron cathode nonuniform emission problem will be more difficult than originally anticipated. After rejecting one of the new cathodes for having significant temperature nonuniformity, the new surface finishing protocol did not alleviate the nonuniform emission observed with previous HPM gyrotron cathodes. However, the new measurement and modeling capabilities developed as part of this research initiative were established as valuable and powerful tools to identify cathode problems before inserting cathodes into the gyrotrons. Meanwhile, our ab initio modeling efforts identified the most likely surface chemistry that explains the high emission efficiency of (some) scandate cathodes and the reasons why this performance is not observed for all scandate cathodes.

2.3. Determine mechanisms and identify solutions to HPM window air breakdown.

UCB and UM collaborated on development of analytic and computational models for window air breakdown, including global, fluid, and fully kinetic models of multipactor and ionization breakdown in noble gases, oxygen, nitrogen, and air. MIT conceived of a way to apply 3D electromagnetic (FEM) models to air breakdown with high power millimeter-wave radiation. TTU developed monte carlo and computational models of the early stages of air and gas breakdown by HPM radiation. TTU developed experimental facilities for research of HPM air breakdown in the vicinity of windows, while MIT did the same for high power millimeter (w-band) radiation. Applying these experimental and modeling capabilities, we identified and quantified most of the primary mechanisms of HPM (microwave) window air breakdown. Models have demonstrated the transition from surface multipactor breakdown to detached volumetric ionization breakdown as a function of gas composition, pressure, and field strength. We have demonstrated the effects of transverse mode structure in expanding the breakdown susceptibility region. Experimental studies of millimeter-wave HPM breakdown observe two dimensional plasma filamentary arrays, with filaments aligned parallel to the electric field and regularly spaced about one-quarter wavelength apare in the place perpendicular to the electric field. Models explain these arrays as resulting from diffraction of the millimeter-wave beam around the filaments. Models accurately predict the experimental observations, including temporal sequencing of filaments, time scales for filament propagation, as well as effects of pressure, field strength, and gas composition on spacing of filaments. From the point of view of breakdown prevention, the fundamental knowledge generated by our research enables designing windows that increases the transmittable power by a factor of several. In fact, in collaborations with AFRL, we have experimentally demonstrated a new window design that increases microwave power by a factor of 3 and microwave pulselength by a factor of 3 in the S-band range of frequencies.

2.4. Manage collaborations and communications, disseminate results, and administer the consortium.

The consortium has functioned very effectively as a collaborative team, as illustrated by some of the references above to collaborative, cross-institutional research. For other notable examples, MIT conducted their millimeter-wave HPM experimental studies in collaboration with TTU, and UCB collaborated with all the other four universities in the development of models and application of models to analyze data. 55 journal papers have been published (or submitted) and 106 conference talks have been presented so far. More will be likely forthcoming in the year or two following the end date of the grant. Seven of the journal papers involve co-authorship between representatives (faculty or students) of different member institutions of the consortium. A large number of other publications involve co-authorship with collaborators in the vacuum electronics industry, DoD research laboratories, or other DoD sponsored university research groups. 19 of the conference talks involve collaborative co-authorship between the 5 consortium universities with another large number of talks co-authored with colleagues at DoD laboratories, vacuum electronics industry, or other DoD sponsored university research groups. Overall, sixteen faculty or staff participated in the research and student mentoring, and 42 students (undergrads, grads, or post-docs) were involved in or supported by this consortium’s research.

3. Summary of Research Highlights and Accomplishments

3.1. Experimental Achievements

3.1.1. Experimental Research Infrastructure Development

During the course of this program, we successfully developed new experimental and research infrastructure as well as exploited existing unique facilities. A new system to study high power microwave (HPM) window and volumetric breakdown at w-band frequencies was established at MIT. A new system for experimental studies of window breakdown at microwave frequencies (2-4 GHz) was developed at TTU. The MAdison Cathode eXperiment (MACX) was established at UW to study vacuum electron field emission. The UM/L3-Titan relativistic magnetron at UM enabled experimental studies of innovative triple point emission cathodes for HPM sources.

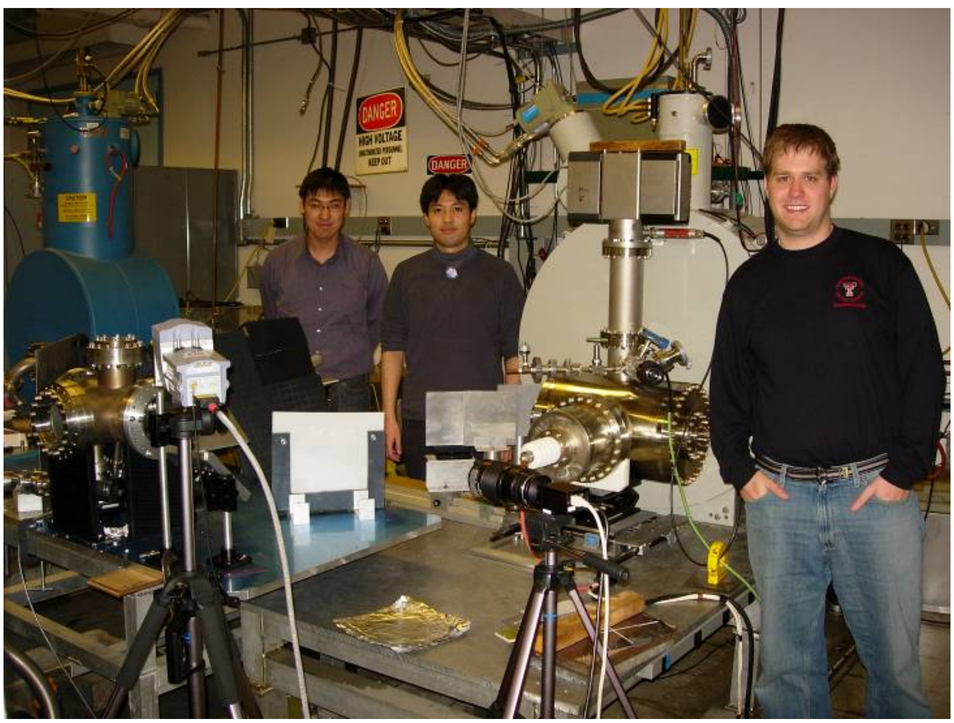


Figure: Experimental set-up for W-band window breakdown research, showing (right to left): Dr. G. Edmiston of Texas Tech University, Dr. Y. Hidaka, MIT and Dr. J. Oda, Univ. of Tokyo

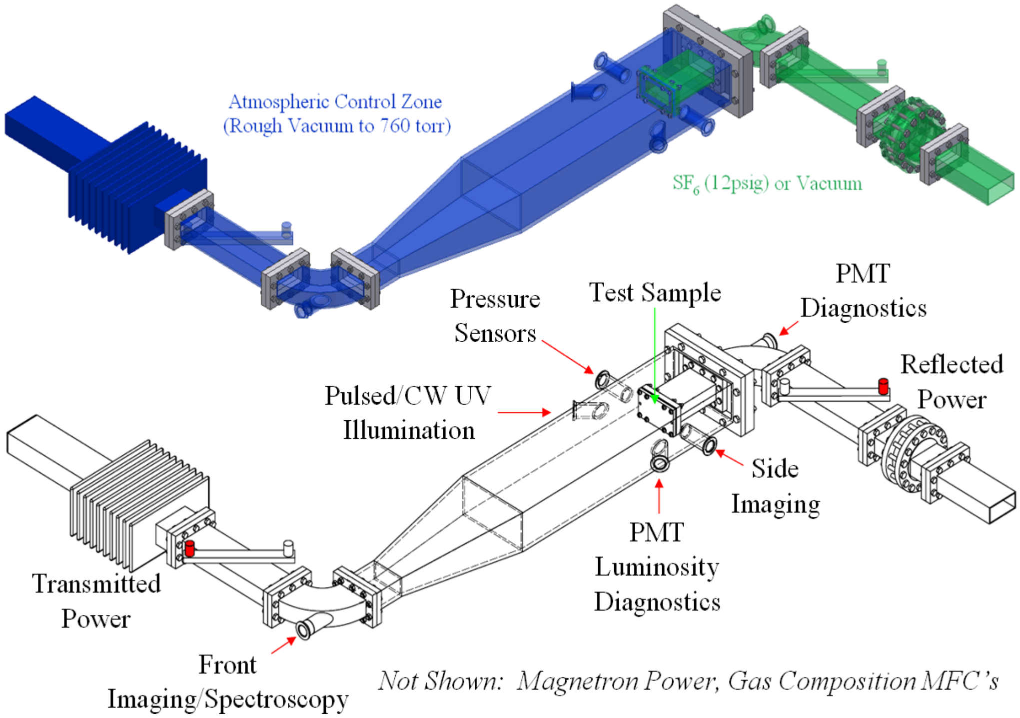


Figure: Facility for HPM window breakdown studies at Texas Tech University

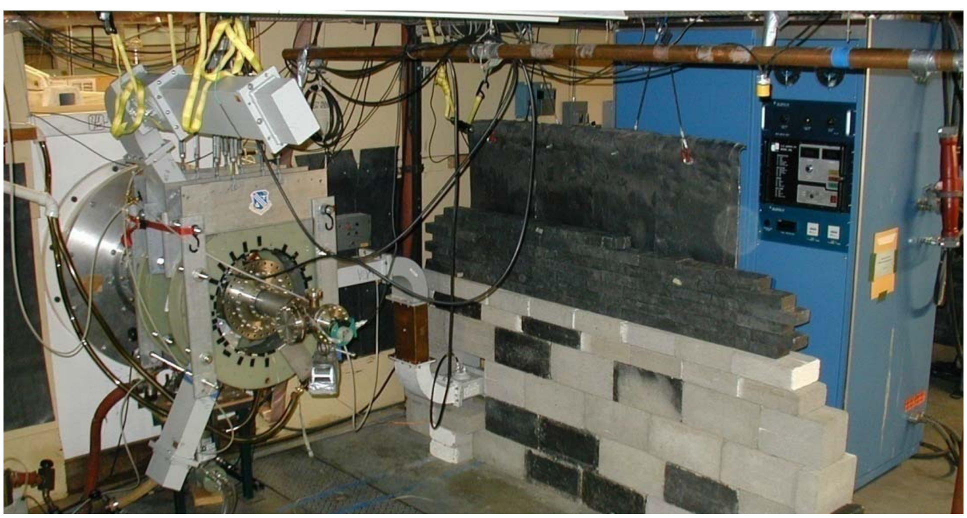


Figure: UM/L3-Titan Relativistic Magnetron with AFRL Microwave Priming Modulator

Figure. Photographs of (left) exterior of the MACX cold cathode research chamber, and (right) cathode positioner showing the coaxial anode/collector.

3.1.2. Formation of plasma filaments during w-band microwave breakdown

Regular, two-dimensional plasma filamentary arrays have been observed in gas breakdown experiments using a pulsed 1.5 MW, 110 GHz gyrotron. The gyrotron Gaussian output beam is focused to an intensity of up to 4 MW/cm^2. The plasma filaments develop in an array with a spacing of about one quarter wavelength, elongated in the electric field direction. The array was imaged using photodiodes; a slow camera, which captures the entire breakdown event; and a fast camera with a six nanosecond window. These diagnostics demonstrate the sequential development of the array propagating back towards the source. Gases studied included air, nitrogen, SF_6, and helium at various pressures. A discrete plasma array structure is observed at high pressure while a diffuse plasma is observed at lower pressure. The propagation speed of the ionization front for air and nitrogen at atmospheric pressure for 3 MW/cm^2 was found to be on the order of 10 km/s.

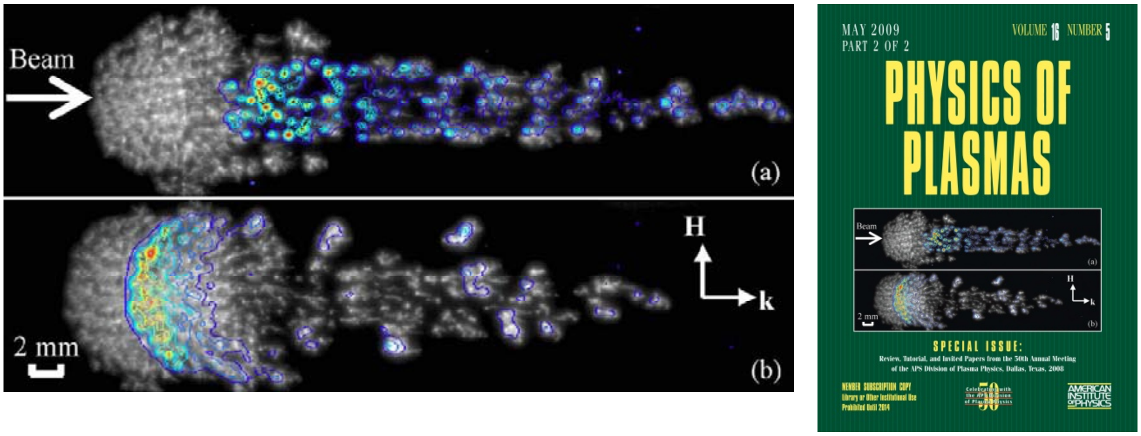
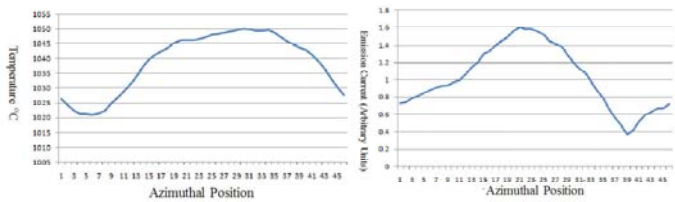


Figure: Images of microwave induced gas breakdown in SF_6 at 115 Torr with 6 ns optical gate pulse starting at (a) t =220 ns and (b) 1.45 microseconds. The black and white images are successive shots with an open shutter showing the entire breakdown event, which is remarkably reproducible. The color images show a 6 ns time window. The images illustrate the progression of the breakdown discharge back towards the source, which is to the left. This photo appeared on the cover of Physics of Fluids, Vol. 16, No. 5, May, 2009.

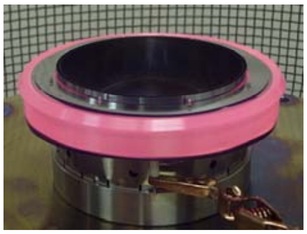
3.1.3. Nonuniform emission from high current density magnetron cathodes

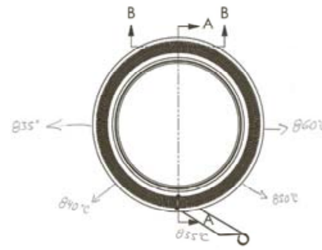
A high quality electron beam is essential for all microwave sources. As the total current requirement increases, both the current density and the area of the cathode increase which present significant challenges in the generation of a uniform electron beam from the entire cathode surface. The electron beam used in gyrotrons is a hollow annular beam and is generated by a Magnetron Injection Gun (MIG). The MIG employs a high current density (~ 1 to 20 A/cm^2) cathode in the form of an annulus operating in the temperature limited regime. Studies at MIT have indicated large variations in the current density of the emitted electron beam along the azimuth. This nonuniformity can lead to enhanced mode competition and reduced efficiency. Extensive studies at MIT on emission nonuniformity revealed that variation in work function was the origin of non-uniform emission in the best cathodes. However, other cathodes with greater emission non-uniformity had emission variation caused by temperature non-uniformity. Calabazas Creek Research has developed a cathode tester that can be used to test gyrotron cathodes for emission nonuniformity. MIT worked with CCR on successfully benchmarking the operation of the cathode tester. The use of the tester can save up to one year in development of a megawatt power level gyrotron by eliminating the possibility of installing a poor cathode in the gyrotron. Such a cathode would have to be replaced with the result of great expense and a delay in testing.



SA1 Cathode

- **Cathode displays significant variation in temperature and current**
- **Cathode cannot be used!!**





SA2 Cathode

- **Bell jar measurements indicate similar T variation as SA1**
- **MIT will seek help from the vendor to correct this problem**

Figure: Two cathodes for a megawatt gyrotron were rejected after being tested in the Calabazas Creek test chamber, due to temperature non-uniformity around the azimuth.

3.1.4. Metal-oxide-junction high current density cold cathodes for HPM sources

To experimentally exploit triple-point emission, metal-oxide junction (MOJ) cathodes consisting of dielectric "islands" over stainless steel substrates were fabricated and studied. The MOJ cathodes were fabricated by ablating a hafnium or magnesium target in a 100 mTorr, 20% O_2, 80% Ar environment. Ablation is achieved by focusing a Lambda Physik Compex 205 KrF excimer laser, with a pulse length of 20 ns and wavelength of 248 nm, onto the surface of a rotating pyramidal target, as shown in *Figure.* . Laser spot sizes ranged from 0.4 mm^2 to 1.3 mm^2, at laser energies from 50 to 300 mJ, resulting in laser fluence between 2 and 40 J/cm^2.

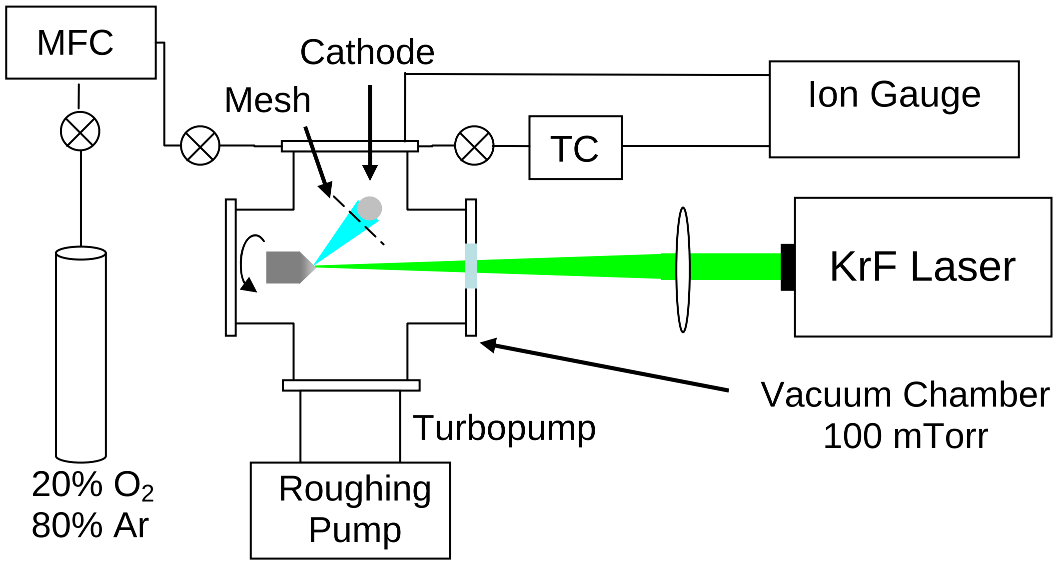


Figure. Basic experimental configuration for all deposition experiments. Vacuum chamber is held at 100 mTorr (Ar/O_2) or ~10^{-6} Torr, depending on the experiment. HV Supply is not used in most experiments.

Using the hafnium and magnesium targets were were able to study the use of two alternative oxides for the dielectric islands: hafnium oxide (HfO_2) for its high dielectric constant, and magnesium oxide (MgO) for its high secondary electron emission coefficient. Cathodes were tested on the Michigan Electron Long-Beam Accelerator-Ceramic (MELBA-C), with a relativistic magnetron, at parameters V=-300 kV, I=1-15 kA, and pulse-lengths of 0.3-0.5 μs. Six variations of the MOJ cathode were tested, and are compared against five baseline cases. It was found that particulate formed during the ablation process improves the electron emission properties of the cathodes by forming additional triple points. Due to extensive electron back-bombardment during magnetron operation, secondary electron emission also may play a significant role. Cathodes exhibit increases in current densities of up to 80 A/cm^2, and up to 15% improvement in current start up time, as compared to polished stainless steel cathodes.

3.1.5. High Power Microwave (2-4 GHz) window breakdown experiments

Microwave frequency (2-4 GHz) window breakdown experiments focused on HPM flashover across a dielectric surface at atmospheric (high pressure) conditions. That is, conditions found if HPM radiation is transmitted through a dielectric window into the atmosphere at altitudes of up to 50,000 feet. Principal results and findings included:

- Expanded the electric field – breakdown delay curves (E/p vs. p*τ) for air, argon, SF_6 from power measurements.
- E/p vs. p*τ curve can be used as baseline prediction for window breakdown in other window geometries
- Determination of the impact of small particles in atmosphere vs. filtered synthetic air

Using a Monte Carlo (MC) code to simulate the electron amplification in the early phase of breakdown and analyze the experimental results, we:

- Demonstrated quantitative agreement with the experiment
- Underlined the importance of electron photoemission due to UV radiation emitted by the discharge
- Improved the understanding of breakdown statistics, production and survival of the first electron
- Further narrowed down influential parameters for breakdown initiation such as surface roughness and humidity

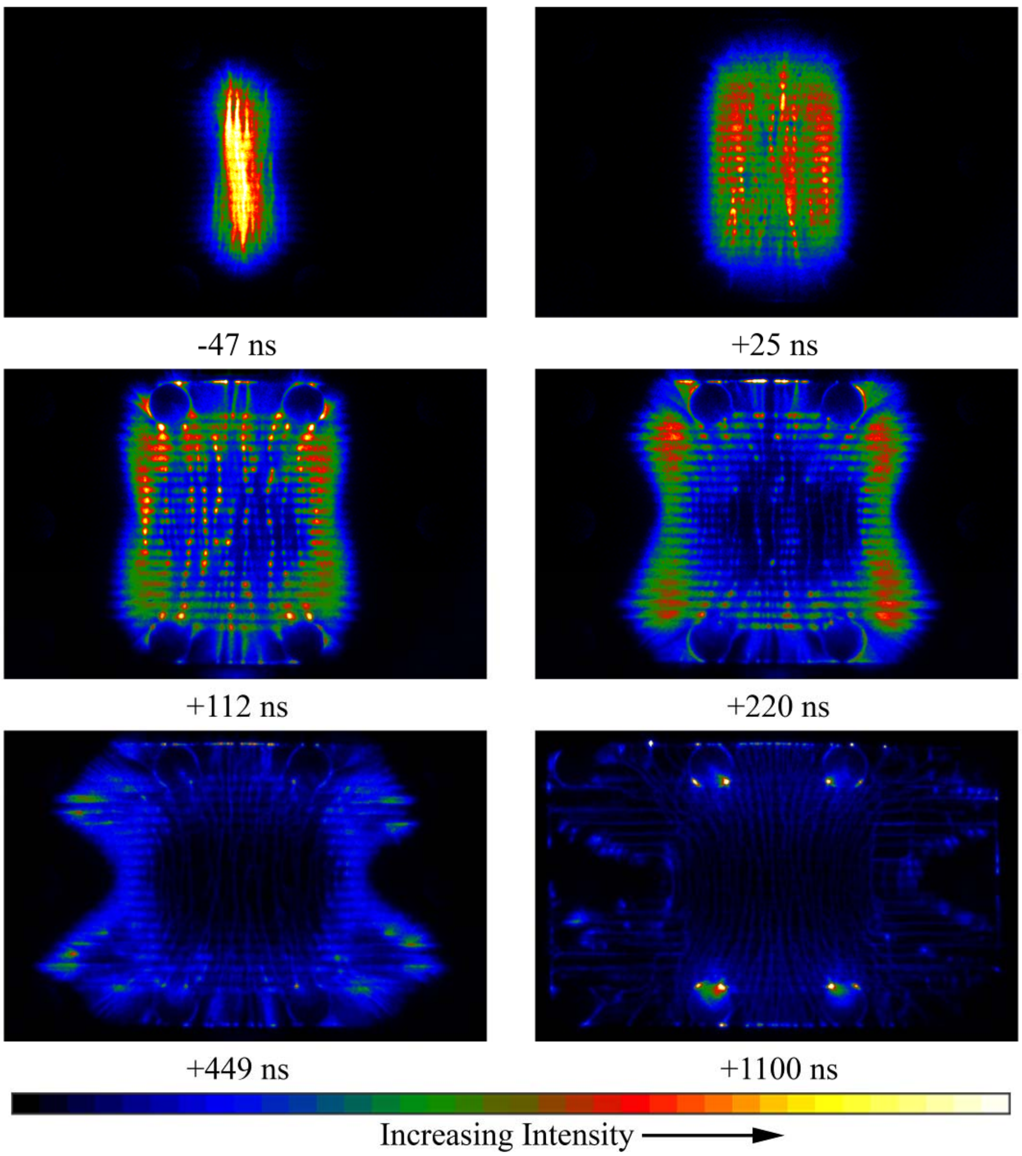


Figure: Development of HPM surface flashover on corrugated polycarbonate window. Time referenced to 50% max luminosity (measured via photomultiplier tube) for a 5 MW, 3.5 μs at 2.85 GHz in air at 120 torr

3.1.6. Vacuum electron field emission studies

The principal findings of experimental studies of vacuum electron field emission included:

- Novel experiments achieving controlled achievement of simultaneous Fowler Nordheim (FN) field and Richardson Laue Dushman (RLD) thermal emission.
- A new Transfer Matrix Method (TMM) analytic-computational model solution of Schrodinger equation was shown to fit the experimental measurements accurately in the high electric field and low electric field regimes over a range of cathode temperatures.
- We established a method to independently extract unambiguous, *in situ* estimates of the effective work function, field enhancement coefficient and E-field-dependent effective emitting area. An example of the E-field-dependent effective emitting area is show in the figure (right) below.

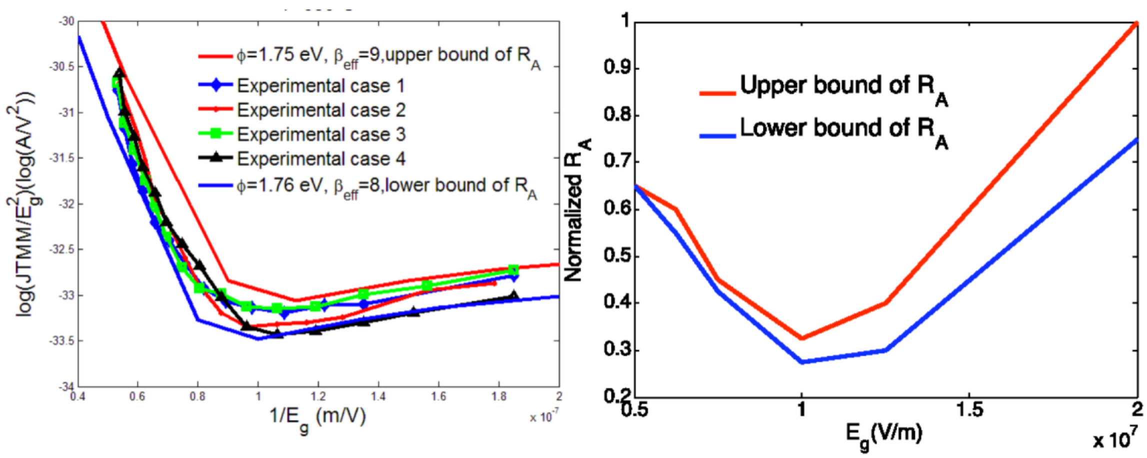


Figure. Point by point matching of four experimental runs with TMM simulation to get upper and lower bounds, (right) variation of effective emission area (ratio) as a function of applied electric field for the two bounds.

- By chemically etching (thinning) copper knife edge (CKE) field emission cathodes, we demonstrated an increase in the emitted current density by two orders of magnitude and increased the cathode-averaged, effective field enhancement factor, β, from approximately 10 to approximately 300-400.
- The chemical etching of the CKE cathodes produced knife edges with nonuniform thicknesses. Using a laterally-movable current collector we were able to correlate locally-emitted currents with the local knife edge thicknesses, as shown below. We were also able to measure 2D current density variations for a single knife edge as shown below.

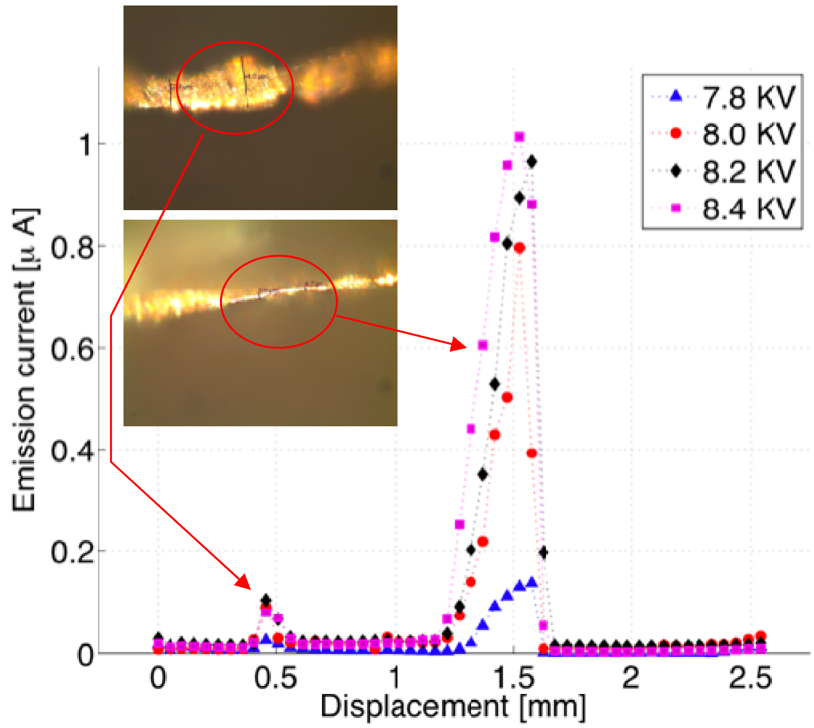


Figure. A lateral scan of the locally-emitted current at different voltages over a chemically etched CKE cathode shows emission from two knife-edges with different local thicknesses.

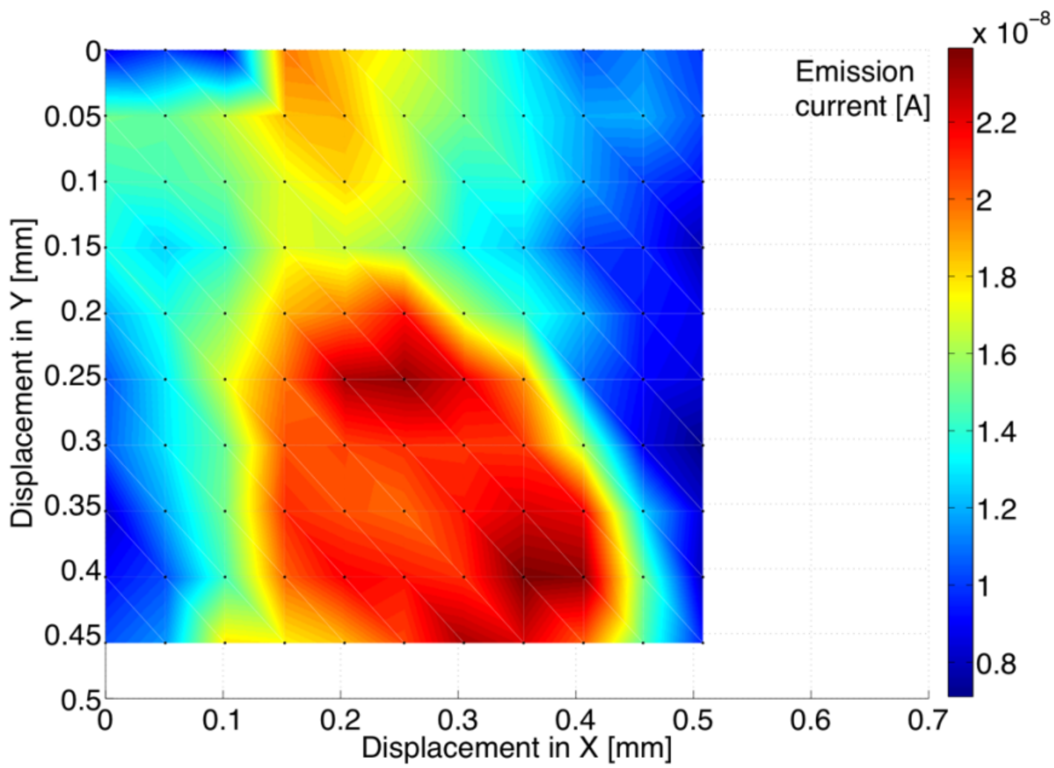


Figure. Local emission current scans over an area on top of a single knife-edge, showing non-uniformity of emission.

- We completed preliminary studies of the effect of coating CKE cathodes with lanthanum hexaboride (LaB_6) films. Crystalline LaB_6 has a bulk work function of ~ 2.7 eV, compared to ~ 4.5 eV for most conducting metals.
- We succeeded in depositing LaB_6 films by DC magnetron sputtering and by performing Kelvin Force Microscopy (KFM) seen that the difference in surface potential in between the copper substrate and the LaB_6 thin film of 1.5 to 2 eV
- Further experiments are in progress to examine the effect of this thin film on the emission currents as a function of voltage as well as temperature

3.2. Theory and Modeling Achievements

3.2.1. Space-Charge Limited Fowler-Nordheim Emission

- We developed a model for numerical model for computing the proper velocity and position of emitted particles in general electric and magnetic fields, for classical and relativistic energies.
- Developed a model for effective field enhancement that allows Fowler-Nordheim field emission to include sub-grid geometric surface features without the cost of resolving them. Also allows modeling geometric features in lower dimensionality, while still preserving the proper emitted current.
- Showed the transition from Fowler-Nordheim field emission toward the suppressed space charge limit, termed Space-Charge Limited Fowler Nordheim (SCL-FN) emission computationally and theoretically. Correctly predicts the local space-charge suppression of the surface electric field, resulting in emitted current below the space charge limit. Also correctly predicts the reduction in effective field enhancement as applied voltage increases. Model also extended to relativistic regime. Results summarized in the Figure below.
- These models allow greatly improved fidelity for modeling field emission processes in intense current density devices.

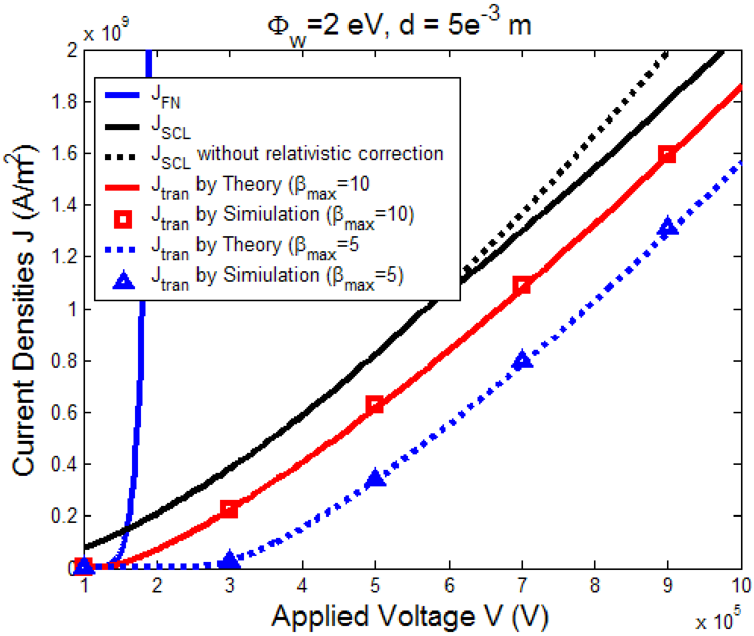


Figure: SCL-FN effects

3.2.2. Microwave Window Breakdown: Transition from Multipactor to Collisional Microwave Discharge

- We have derived the theoretical scaling laws for dielectric window breakdown in vacuum and collisional regimes for Ar, Ne, and Xe. Noble gases were chosen for this initial study for the simplicity in the chemistry; their ionization and other collision cross-sections are well characterized and straightforward (compared with air). The initiation time of radio frequency (RF) window breakdown was obtained for each of these three gases. They apply to the vacuum, multipactor-triggered regime and to the collisional RF plasma regime, and they are corroborated by computer simulations on these three gases over a wide range of pressures. This work elucidates the key factors that are needed for the prediction of RF window breakdown in complex gases, such as air, at various pressures.
- We developed a computational model for reflection, absorption, and transmission of electromagnetic plane waves for plasma slabs with arbitrary density profiles.
- We developed a PIC model for multipactor breakdown which demonstrated temporal oscillation between growth and decay. Also showed spatial dependence of multipactor density profiles, as well as dependence on spatially dependent driving fields.
- We demonstrated that the transition from low pressure multipactor to high pressure collisional microwave discharge occurs at about 50 Torr, as shown in the figure below.

Breakdown time trends are consistent with experimental results for many noble gases, nitrogen, oxygen, and air.

- We developed a spatially independent global model for collisional breakdown in gases which includes a kinetic electron energy distribution function (EEDF) based on results from a kinetic PIC model. The EEDF was found to be a function of cross sections only for most gases over four decades in pressure, with some dependence on frequency for Ramsauer gases. Global model achieves excellent agreement with the kinetic model in minutes, compared to days for the full model, as shown below.
- These models and results explain the fundamental physics of microwave window breakdown across four decades in pressure.

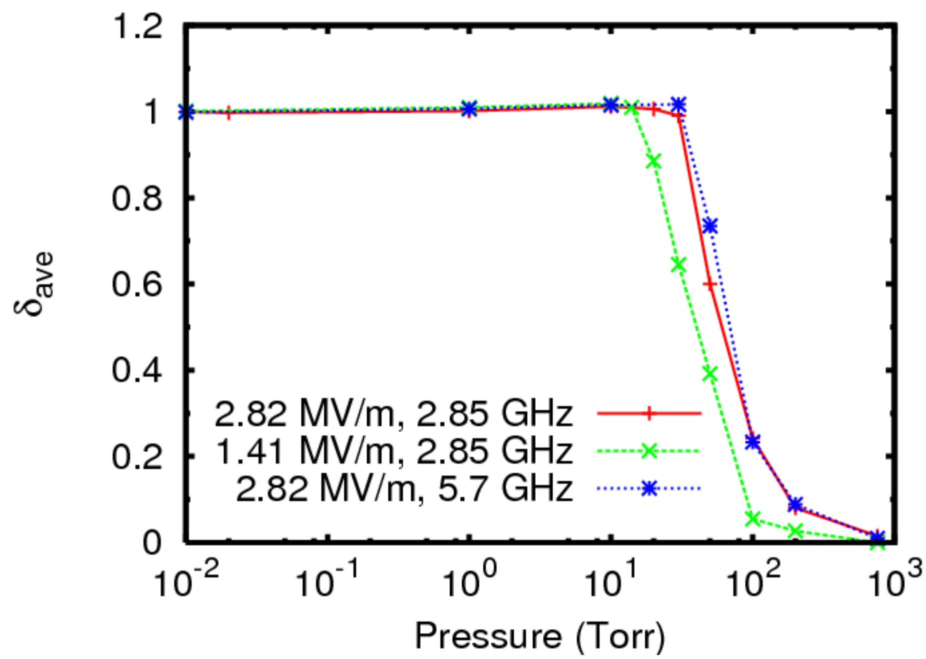


Figure: Transition from multipactor to collision discharge occurs at 10-50 Torr.

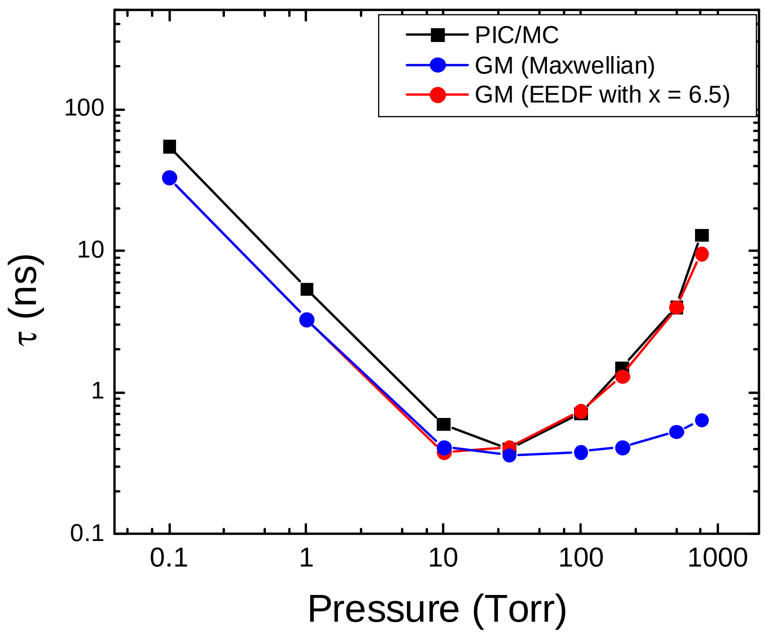


Figure: Enhanced global model reproduces kinetic PIC result.

3.2.3. The physics of plasma filaments formed during w-band microwave breakdown

- We developed an explanation for experimentally observed filaments using a fluid model based on the enhanced global model and the electromagnetic wave model, in atmospheric pressure air.
- We showed the temporal evolution of the fields, density and emitted light, as shown in the Figure below.
- We explained the sequential formation of filaments spaced at one quarter wavelength.
- These models demonstrate the capabilities of the breakdown models developed in this program to explain unanticipated phenomena.

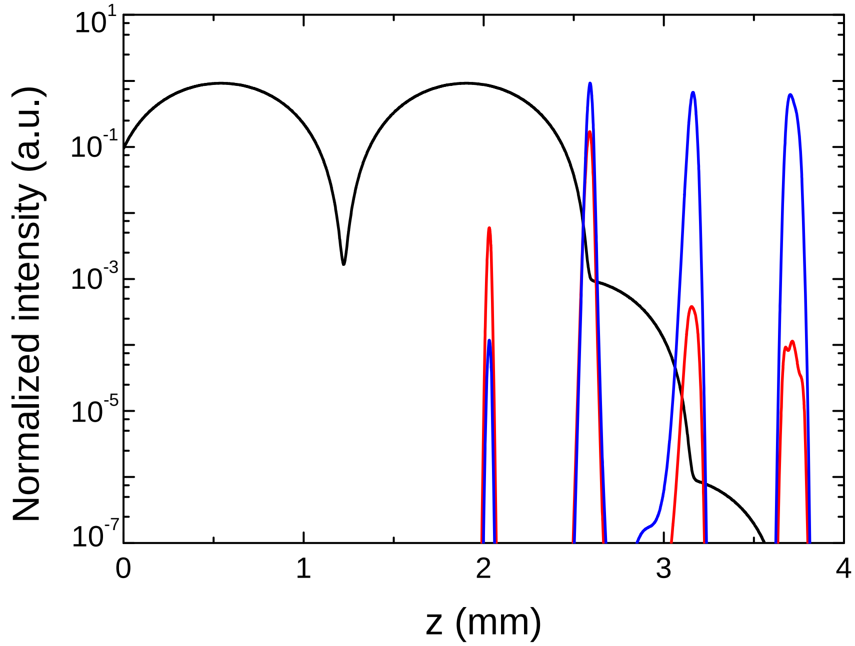


Figure: Electric field strength (black), filament electron density (blue), and light emission (red) results at one instant of time during the simulated formation of plasma filaments from w-band microwave breakdown.

3.2.4. Triple-point-emission and triple-point-emission cathodes

A triple point is defined as the junction of metal, dielectric, and vacuum. This is the location where electron emission is favored in the presence of a sufficiently strong electric field, hence its utilization in the MOJ cathodes. In addition to being an electron source, the triple point is generally regarded as the location where flashover is initiated in high voltage insulation, and as the vulnerable spot from which rf breakdown is triggered. Our theoretical research has shown that despite the mathematically divergent electric field at the triple point, significant electron yield most likely results from secondary electron emission when the seed electrons strike the dielectric. Our theory gives the voltage scale in which this electron multiplication may occur. It also provides an explanation on why certain dielectric angles are more favorable to electron generation over others, as observed in previous experiments.

3.2.5. Cross-field diode closure due to presence of ions

Using theoretical charged particle trajectory models, we unearthed an unsuspected, novel mechanism of crossed-field diode closure. The effect of ions in a crossed-field gap is studied using single particle orbit model, shear flow model, and particle-in-cell simulation. It is found that, in general, the presence of ions in a crossed-field gap always increases the electrons' excursion toward the anode region, regardless of the location of the ions. Thus, the rate at which the electrons migrate toward the anode, which is a measure of diode closure rate, is related to the rate at which ions are introduced into the crossed-field gap. This anode-migration of electrons is unrelated to crossed-field ambipolar diffusion. This newly discovered effect has important implications for pulse shortening in relativistic magnetrons and bipolar flows in pulsed-power systems.

3.2.6. Field enhancement on simple and complex conducting knife-edges.

We have obtained exact analytic expressions for the electric field enhancement by simple and complex knife-edge electron field emitters.. We used conformal mapping to first calculate the electric field on a knife-edge cathode, modeled as a rectangular ridge on a flat surface. We found that the field enhancement factor scales approximately as the square root of the height-to-width ratio of the knife-edge. A simple analytic approximation for the divergent electric field in the immediate vicinity of the sharp edge was derived. When a smaller knife-edge is placed on top of a larger one, both assumed to have large height-to-width ratios, the composite field enhancement factor was shown to be approximately equal to the product of the field enhancement factor of the individual knife-edges, thereby proving Schottky's conjecture on multiplication of field enhancement factors for one special case. Most recently, we found that Schottky's conjecture is in general valid if the height of the upper knife-edge is less than the width of the lower knife-edge.

3.2.7. Field enhancement and additional rf ohmic heating due to localized surface roughness

We derived a theoretical model that predicts the additional heating, as well as the local RF electric field and RF magnetic field enhancements due to small, localized surface roughness. This problem is very important as surface roughness may exert a profound effect in the performance of radio-frequency (RF) cavities or slow wave structures. It may cause enhanced power absorption. It may also lead to excessive local electric field enhancement that triggers RF breakdown. In a superconducting cavity, surface roughness may also cause local magnetic field enhancement that leads to abrupt quenching, i.e., rapid loss of superconductivity. We have established the scaling laws for a small hemispherical surface protrusion of radius a, with arbitrary values of ε, μ, and σ, and these scaling laws have been spot-checked against the Maxwell-3D code. In general, the heating by the RF magnetic field in the surface protrusion is dominant when $\delta/a < 1$, even for nonmagnetic materials, where δ is the skin depth associated with the protrusion material.

The field enhancement factors for both the RF electric field and the RF magnetic field on the protrusion are also calculated analytically. These field enhancement factors are also consistent with the published results in the $\delta = 0$ limit, in which case the protrusion may represent a small local bump on the surface of a superconducting cavity.

3.2.8. A higher dimensional theory of electrical contact resistance

We have developed and experimentally verified a higher dimensional theory of electrical contact resistance. This is the first novel advance in this subject in more than forty years. Electrical contact is an important issue for field emitters, metal-insulator-vacuum junctions, high power microwave sources, pulsed power systems, thin film resistors, and also in wafer evaluation of manufactured integrated circuits, etc. As pointed out to us by Dr. Mike Haworth of AFRL, successful operation of high power microwave sources such as the relativistic magnetrons depends crucially on good RF contacts. We generalize the classical Holm-Timsit theory of contact resistance to higher dimensions, by allowing the electrical contact (in the form of a small connecting bridge between two metallic blocks) to have a finite length in the direction of the current flow.

3.2.9. Effects of electrically-polarized surface films on work function and electron emission from cold and hot high current density cathodes

We have used a combined ab initio and surface science approach to understand how surface modification of cathodes improves their emission properties. We have developed ab initio based modeling approaches to predict properties of surface coatings on cathode surfaces, including stability and work function. We have combined these modeling approaches with a number of experimental surface characterization techniques, including Energy Dispersive X-ray Spectroscopy (EDS) and Scanning Auger Spectroscopy (SAM). We have used these approaches to

- Demonstrate a number of basic properties of cathode work function modification by surface layers, including i) that surface layer work function modification is almost perfectly described by the Helmholtz equation, which relates surface dipole moments to changes in work function, and ii) that depolarization theories are quite accurate except when surface geometries change or dipoles interact quantum mechanically at high coverage.
- Determine the mechanisms by which CsI coatings enhance the field emission of carbon fibers. Our combined ab initio and experimental approaches confirmed that Cs-O compounds dominate the surface of coated fibers and can explain both reduced turn on fields (through lowered work function) and increased emission (through secondary electron emission). Surprisingly, no I was found on the surface, overturning the intuitive idea that Cs-I dipoles are playing a key role. The absence of I was explained through ab

initio based prediction of preferential loss of I due to formation and weak binding of H-I molecules.

- Predict coating properties and their relation to function of B-type and scandate thermionic cathodes. B-type cathodes work by creating B_xO_y monolayers on a W surface to lower the W work function. We established that active B-type cathode work functions are likely covered by about ¼-½ monolayer of Ba-O dipoles, and that these dipoles are tilted in orientation with respect to the surface. However, we also found that the most stable and lowest work function structure of Ba and O on the W surface was a $Ba_{0.25}O_1$ structure. This result demonstrates for the first time that the classic B-type cathode system has a steady state surface structure different from that which would occur at equilibrium. This may be a fundamental property of many thermionic cathode surfaces. Some of the key predictions of Ba_xO_y work functions and comparison to experiments are shown in the figure below. Addition of Sc to the surface structure yielded a very stable $Ba_{0.25}Sc_{0.25}O_1$ monolayer structure with a work function very close to the measured value for scandate cathodes. We therefore proposed that this $Ba_{0.25}Sc_{0.25}O_1$ could play a key role in the exceptional performance of scandate thermionic cathodes.

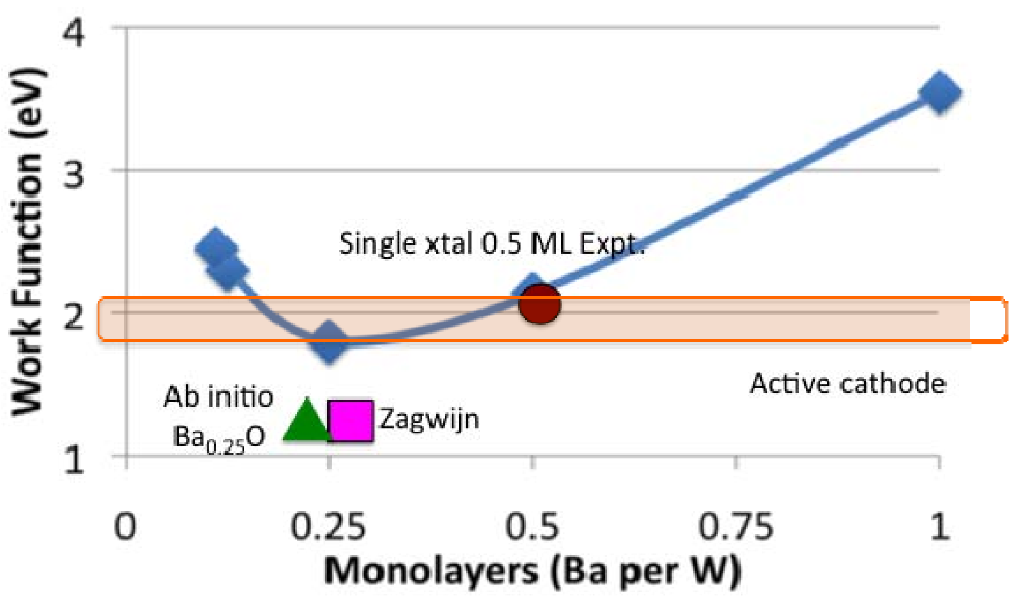


Figure: Comparison of ab initio predicted and experimental work functions for Ba-O monolayers on W. The blue diamonds show work function values for Ba-O dimers, demonstrating that the predictions match the active cathode work function for ¼ - ½ a monolayer coverage. This result is also consistent with ½ monolayer work function values from experiments (red circle, from refs [R. Forman, Appl. Surf.Sci. 2, 258 (1979); G.A. Haas, et al., Appl. Surf. Sci. 16, 139 (1983)]. The most stable and lowest work function structure we predict is for a $Ba_{0.25}O$ structure (green triangle), which is consistent with a similar surface coating measured by Zagwijn (pink square) [P.M. Zagwijn, J.W.M. Frenken, U. van Slooten, and P.A. Duine, Appl. Surf. Sci. 111, 35 (1997)]. These results demonstrate that ab initio methods are a powerful tool for interpreting experimental data on cathode surface properties and accurately predicting surface structures.

4. Personnel Supported

4.1. UC-Berkeley

Prof. John Verboncoeur (faculty)
Prof. Charles K. Birdsall (faculty)
Dr. Hyun-Chul Kim (postdoc)
Dr. Sangki Nam (postdoc)
Yang Feng (PhD student)
Chul-Hyun Lim (PhD student)
Jeff Hammel (PhD student)
Christine Nguyen (MS student)
Ye Chen (PhD student)
Jonathan Noland (PhD Student)
Ying Wang (PhD student)
Benjamin Ragan-Kelly (PhD student)
Manuel Aldan (PhD student)
Austin Minnich (BS student)
Soren Taverniers (BS student)

4.2. MIT

Richard Temkin	Associate Director, Plasma Science and Fusion Center
Michael Shapiro	Research Scientist
Jagadishwar Sirigiri	Research Scientist
Ivan Mastovsky	Engineer
William Mulligan	Engineer
Yoshiteru Hidaka	Postdoctoral Associate
Seong Tae Han	Postdoctoral Associate
Eunmi Choi	Grad Student – Ph. D.
Chad Marchewka	Grad Student - Masters
Antoine Cerfon	Grad Student – Ph. D.
E. Nicholas Comfoltey	Grad Student - Masters
Colin Joye	Grad Student – Ph. D.
Roark Marsh	Grad Student – Ph. D.
David Tax	Grad Student – Ph. D.
Antonio Torrezan	Grad Student – Ph. D.
Elizabeth Kowalski	Grad Student – Ph. D.
Emilio Nanni	Grad Student – Ph. D.
Brian Munroe	Grad Student – Ph. D.
Jason Bryslawskij	Undergrad Student

4.3. University of Michigan

R.M. Gilgenbach, Professor
Y.Y. Lau, Professor
Michael Jones, Doctoral Graduate, 2005
Nick Jordan, Doctoral Graduate, 2008

4.4. Texas Tech University

Dr. Andreas A. Neuber, PI, advisor
Dr. James C. Dickens, Co-PI
Dr. Hermann Krompholz
Dr. John Krile, post-doctoral research associate
John Krile, Ph. D. Student EE
Greg Edmiston, Ph. D. Student EE
Luke McQuage, MS Graduate Student
Jonathan Foster, MS Graduate Student
Mark Thomas, MS Graduate Student
Garrett Rogers, MS Graduate Student
George Laity, MS Graduate Student
Darren Santeler, Undergraduate Student
Daniel Garcia, technician

4.5. University of Wisconsin

John Booske, Professor
John E. Scharer, Professor
Dane Morgan, Professor
Xin He, Graduate Student
Nishant Sule, Graduate Student
Vasilios Vlahos, Graduate Student
Ryan Miller, Graduate Student
Sean Sengele, Graduate Student
Eric Meunier, Undergraduate Student

5. Publications

5.1. Journal publications

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5.2. Conference Papers, Talks, and Abstracts

1. Booske, J. H., He, X., Miller, R.L., Morgan, D., Scharer, J.E., Vlahos, V., Gilgenbach, R.M., Jordan, N., Lau, Y.-Y., Feng, Y., and Verboncoeur, J., "Innovations and Fundamental Insights of Advanced Field Emission Cathodes for High Power Microwave (HPM) Sources", 34th IEEE ICOPS, Albuquerque, NM (2007) invited.
2. Booske, J.H., Scharer, J.E., He, X., Vlahos, V., He, X., “High Current Density Advanced Cathode Facility,” American Physical Society Division of Plasma Physics Annual Meeting, Savannah, GA, 15-19 Nov, (2004).
3. Booske, J.H., “Innovations and fundamental insights of advanced field emission cathodes for high power microwave sources,” **invited tutorial lecture**, International Vacuum Nanoelectronics Conference, Chicago, IL, July 8-12 (2007).
4. Booske, J.H., “Plasma Physics Challenges of MMWave-to-THz and High Power Microwave Generation,” **Invited Plenary Review Talk**, 49th Annual Meeting, American Physical Society’s Division of Plasma Physics, November 12-16, (2007).
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(HPM) sources,**”**, **Invited Talk**, IEEE Pulse Power and Plasma Science Conference, Albuquerque, NM , June 17-22, (2007).

6. Booske, J.H., Vlahos, V., Morgan, D.D., “Low work function HPM graphite cathodes coated with alkali and alkaline-earth elements and compounds,” American Physical Society Division of Plasma Physics 48th Annual Meeting, Philadelphia, PA, Oct 30-Nov 3, (2006).
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11. Edmiston, G., Neuber, A., Krompholz, H., Dickens, J., Krile, J., "High Power Microwave Surface Flashover of a Gas-Dielectric Interface at 90 to 760 Torr," oral presentation, published in the Proceedings of the *15th Int. IEEE Pulsed Power Conference*, Monterey, CA, June 13-17, (2005).
12. Feng, Y. and Verboncoeur, J.P., "Solution for Space-Charge-Limited Currents in Initially Monoenergetic Electron Vacuum Diodes in the Relativisitic Regime", 34th IEEE ICOPS, Albuquerque, NM (2007).
13. Feng, Y. and Verboncoeur, J.P., “A model for effective field enhancement for Fowler-Nordheim field emission”, 32nd IEEE ICOPS, Monterey, CA USA (2005).
14. Feng, Y. and Verboncoeur, J.P., “Transition from Fowler-Nordheim field emission to space charge limited current density”, 32nd IEEE ICOPS, Monterey, CA USA (2005).
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25. He, X., Vlahos, V., Scharer, J., Booske, J., Sengele, S., Jordan, N., Gilgenbach, R., “Experimental measurements of electron emission uniformity from cold cathodes,” American Physical Society Division of Plasma Physics 48th Annual Meeting Philadelphia, PA, Oct 30-Nov 3, (2006).
26. He, X., Vlahos, V., Scharer, J., Booske, J., Sengele, S., Miller, R., Jordan, N., Gilgenbach, R., “High Current Density Advanced Cold Cathode Experiments,” IEEE International Vacuum Electronics Conference and IEEE International Vacuum Electron Sources Conference, IVEC/IVESC 2006, 25-27 April, Monterey, CA, (2006).
27. Hidaka, Y., “Observations of Regular Filamentary Plasma Arrays in High-Pressure Gas Breakdown by 1.5 MW, 110 GHz Gyrotron Pulses”,APS Div. Plasma Physics, Dallas, TX USA. (Nov.2008) **Invited (Abstract)**.
28. Hidaka, Y., Choi, E., Mastovsky, I., Shapiro, M.A., Joye, C.D., Jagadishwar, R.S., Sirigiri, R., Temkin, R.J., “Experimental Investigation of Filamentary Arrays in a Breakdown Plasma Generated by a 1.5 MW, 110 GHz Gyrotron Pulsed Power Plasma Science, 2007. PPPS 2007. Conference Record - Abstracts. IEEE 17-22 Page(s):903 – 903 (June 2007).
29. Hidaka, Y.; Choi, E.M., Mastovsky, I., Shapiro, M.A., Sirigiri, J.R., Temkin, R.J., “Filamentary arrays in breakdown plasmas generated by a 1.5 MW, 110 GHz Gyrotron Infrared and Millimeter Waves, 2007 and the 2007 15th International Conference on Terahertz Electronics. IRMMW-THz. Joint”, 32nd International Conference Page(s):516 - 517 on; 2-9 Sept.,(2007)
30. Hoff, B.W., Gilgenbach, R.M., Lau, Y.Y., Cruz, E.J., White, W., Jordan, N.M., Cartwright, K.L., Mardahl, P., Fleming, T., Haworth, M.D., Spencer, T.A., and Price, D., “Magnetic priming of relativistic magnetron using ferromagnetic wires in cathode

and anode," PPPS-ICOPS (Albuquerque, NM) Conference Record, paper 5P19 (June, 2007).
31. Hoff, B.; Gilgenbach, R.M.; Lau, Y.Y.; French, D.; Franzi, M.A.; Haworth, M.D.; Mardahl, P., " Dielectric Window Breakdown on the UM/L-3 Relativistic Magnetron," Bull. Am. Phys. Soc. **53**, No. 14, p. 302 (2008).
32. Jordan, N.M.; Lau, Y.Y.; French, D.M.; Gilgenbach, R.M.; Pengvanich, P., "Electron Emission Near a Triple Point," in Conference Abstract of 2008 IEEE International Vacuum Electronics Conference (Monterey, CA) , p. 288 (2008).
33. Jordan, N.M.; Gilgenbach, R.M.; Lau, Y.Y.; Hoff, B.W.; Cruz, E.J.; French, D.M.; Gomez, M.R.; Pengvanich, P.; Zier, J., "METAL-OXIDE-JUNCTION, TRIPLE-POINT CATHODES FOR HIGH CURRENT VACUUM ELECTRON DEVICES," in 2007 IEEE International Pulsed Power and Plasma Science Conference, Paper 3P40 (Albuquerque, NM, 2008).
34. Kim, H. C., Verboncoeur, J. P., Edmiston, G., Neuber, A. A., Lau, Y. Y., and Gilgenbach, R. M.,"Transition of Window Breakdown from the Vacuum Multipactor Discharge to the Collisional RF Plasma," published in the Proceedings of the 7th International Vacuum Electronics Conference, Monterey, CA, April 25-27, (2006.)
35. Kim, H.-C. and Verboncoeur, J.P., "Validity of Two-Term Boltzmann Approximation Employed in Fluid Models", 34th IEEE ICOPS, Albuquerque, NM (2007).
36. Kim, H.C. and Verboncoeur, J.P., "Physics of a single-surface multipactor discharge," *International Conference on Computational Physics*, Gyeongju Korea (2006), invited.
37. Kim, H.C. and Verboncoeur, J.P., "Effect of electron-neutral collisions in multipactor discharge on a dielectric", 32nd IEEE ICOPS, Monterey, CA USA (2005).
38. Kim, H.C. and Verboncoeur, J.P., "Modeling of RF Window Breakdown," *International Conference on Computational Physics*, Gyeongju Korea (2006), invited.
39. Kim, H.C., Chen, Y., and Verboncoeur, J.P., "Electromagnetic effect on a discharge generated in the window breakdown on a dielectric", Bull Am. Phys. Soc. 51, 56 (2006).
40. Kim, H.C., Chen, Y., Verboncoeur, J.P., and Lau, Y.Y., "Electromagnetic and 3d effects in the multipactor discharge on a dielectric," *7th IEEE International Vacuum Electronics Conference*, Monterey, CA USA (2006).
41. Kim, H.C., Verboncoeur, J.P., Edmiston, G.F., Neuber, A.A., Lau, Y.Y., and Gilgenbach, R.M., "Transition of window breakdown from the vacuum multipactor discharge to the collision rf plasma", *7th IEEE International Vacuum Electronics Conference*, Monterey, CA USA (2006), *keynote*.
42. Krile, J., Edmiston, G., Dickens, J., Krompholz, H., and Neuber, A., "Window Flashover Initiation Under Pulsed Microwave Excitation," to be published in the Proceedings of the 2008 IEEE International Power Modulator Conference Las Vegas, Nevada, USA, May 27-31, (2008).
43. Krile, J., Neuber, A., Dickens, J., Krompholz, H., Edmiston, G., "Similarities of Dielectric Surface Flashover at Atmospheric Conditions for Pulsed Unipolar and RF Excitation," oral presentation, published in the Proceedings of the *15th Int. IEEE Pulsed Power Conference*, Monterey, CA, June 13-17, (2005).

44. Krile, J., Neuber, A., Edmiston, G., Dickens, J., “Surface Flashover under RF and Unipolar Excitation at Atmospheric Conditions”, presented at the 27th Power Modulator Symposium and 2006 High Voltage Workshop, Washington, DC, May 14-18, (2006)*invited.*
45. Krile, J.T., Neuber, A. A., Krompholz, H.G., "Effects of UV Illumination on Surface Flashover under Pulsed Unipolar Excitation," presented at the 2007 IEEE Pulsed Power and Plasma Science Conference, Albuquerque, NM June 17-22, (2007)*invited.*
46. Lim, C.-H. and Verboncoeur, J.P., "Modeling X-Ray Emission in a High Voltage Vacuum Gap Including Secondary Electron Emission", 34th IEEE ICOPS, Albuquerque, NM (2007).
47. Lim, C.H. and Verboncoeur, J.P., “Relativistic collision model for particle simulation”, 32nd IEEE ICOPS, Monterey, CA USA (2005).
48. Lim, C.-H. and Verboncoeur, J.P., “X-ray generation in energetic surface impact for the particle simulation model of plasmas”, *7th IEEE International Vacuum Electronics Conference*, Monterey, CA USA (2006).
49. Lin, M.-C., Chang, P. C., and Verboncoeur, J. P., "Infuence of ion effects on a space charge limited field emission flow: from nonrelativistic classical to ultrarelativistic regimes", 36th IEEE ICOPS, San Diego, CA (2009).
50. Luginsland, J. W., Lau, Y. Y., Cartwright, K. L., Haworth, M. D., “Ions and their impact on gap closure and pulse shortening in high power crossed-field diodes,” PPPS-ICOPS (Albuquerque, NM) Conference Record, paper 4E4 (June, 2007).
51. Marchewka, C.D. (MIT Plasma Sci. & Fusion Center, Cambridge, MA, USA); Petillo, J.J., Shapiro, M.A., Sirigiri, J.R., Temkin, R.J., “Nonuniform cathode emission studies of a MIG gun”, The Joint 30th International Conference on Infrared and Millimeter Waves (IEEE Cat. No. 05EX1150), p 612-13 vol. 2, (2005).
52. McQuage, L. M., Edmiston, G., Mankowski, J. P., Neuber, A. A., "Short Pulse High Power Microwave Surface Flashover," presented at the 2007 IEEE Pulsed Power and Plasma Science Conference, Albuquerque, NM June 17-22, (2007).
53. Miller, R., Lau, Y.Y., and Booske, J.H., “Effective current enhancement vs. aspect ratio for rectangular ridge cathodes,” IEEE Pulse Power and Plasma Science Conference, June 17-22, Albuquerque, NM (2007).
54. Miller, R., Lau, Y.Y., and Booske, J.H., “Effective Current Enhancement vs. Aspect Ratio for Rectangular Ridge Cathodes,” International Vacuum Nanoelectronics Conference, Chicago, IL, July 8-12 (2007).
55. Miller, R., Lau, Y.Y., Booske, J.H., “Field Enhancement on Knife-Edge Cathodes,” IEEE International Vacuum Electronics Conference, Monterey, CA, April 22-24 (2008).
56. Miller, Ryan, Lau, Y.Y., Booske, John H., “Calculation of ridge electric field enhancement on field emission cathodes,” Bull. Am. Phys. Soc. **53**, No. 14, p. 243 (2008).
57. Morales, K., Krile, J., Neuber, A., Dickens, J., Krompholz, H., “Pulsed Unipolar Surface Flashover At Atmospheric Conditions ”, presented at the 27th Power Modulator Symposium and 2006 High Voltage Workshop, Washington, DC, May 14-18, (2006) *invited*.

58. Nam, S. K. and Verboncoeur, J. P., "Theory of filamentary plasma array formation in microwave breakdown at near atmospheric pressure", 36th IEEE ICOPS, San Diego, CA (2009).
59. Nam, S. K. and Verboncoeur, J.P., "Effect of electron energy distribution function on the global model for high power microwave breakdown at high pressures", 2008 IEEE IVEC, Monterey, CA USA (2008).
60. Nam, S. K. and Verboncoeur, J.P., "Effect of Electron Energy Distribution Function on Global Model for High Power Microwave Breakdown at High Pressure", 61st Gaseous Electronics Conference, Dallas, TX USA (2008).
61. Nam, S. K. and Verboncoeur, J.P., "Global Model for High Power Microwave Breakdown at High Pressure", 29th IEEE IPMC, Las Vegas, NV USA (2008).
62. Nam, S. K., Lim, C., Verboncoeur, J.P., and Kim, H.C., "Dielectric window breakdown in oxygen gas: from vacuum multipactor to collisional microwave discharge", Bull. Am. Phys. Soc. **52**, 197 (2007).
63. Nam, S. K., Lim, C.-H., and Verboncoeur, J.P., “Two-dimensional Effects in High Power Microwave Breakdown", 61st Gaseous Electronics Conference, Dallas, TX USA (2008).
64. Neuber, A., “Dielectric Surface Flashover at Atmospheric Conditions under High Power Microwave Excitation,” APS conference, 2006 48th Annual Meeting of the Division of Plasma Physics, Meeting Id: DPP06, Philadelphia, PA, October 30-November 3, (2006) *invited.*
65. Neuber, A., “Dielectric Surface Flashover at Atmospheric Conditions under High Power Microwave Excitation,” 2006 48th Annual Meeting of the Division of Plasma Physics, Meeting Id: DPP06, Philadelphia, PA, October 30-November 3, (2006) *invited.*
66. Neuber, A., “Dielectric Surface Flashover under Pulsed Unipolar and RF Excitation,” presented at the DPG Frühjahrstagung des AMOP, Düsseldorf, Germany, March 19-23, 2007, *(invited plenary presentation)*
67. Neuber, A., Edmiston, G., Krile, J., Foster, J., Krompholz, H., “Statistics of High Power Microwave Induced Window Flashover,” presented at the 35th IEEE International Conference on Plasma Science, Karlsruhe, Germany ,June 15-19,(2008).
68. Neuber, A., Krile, J., Edmiston, G., Krompholz, H., Dickens, J., M. Kristiansen, M., “Interface Breakdown During High Power Microwave Transmission,” to be published in the proceedings of the 13th EML Symposium, Berlin,Germany, May 22-25, (2006).
69. Neuber, A., Krile, J., Edmiston, G., Krompholz, H., Dickens, J., Kristiansen, M., “Interface Breakdown During High Power Microwave Transmission,” presented at the 13th EML Symposium, Berlin, Germany, May 22-25, (2006).
70. Neuber, A., Krompholz, H., Dickens, J., Kristiansen, M., “Dielectric Surface Flashover Research at Texas Tech University,” to be presented at the 1st Euro-Asian Pulsed Power Conference, Chengdu, China , Sept. 18 -22, (2006) *invited.*
71. Nguyen, C., Lim, C.-H., and Verboncoeur, J.P., "A collision scheme for hybrid fluid-particle simulation of plasmas", Bull Am. Phys. Soc. 51, 168 (2006).
72. Pengvanich, P., Lau, Y. Y., Chernin, D., Gilgenbach, R. M., Luginsland, J. W., “Effects of random manufacturing errors on small signal gain and phase in a TWT,” PPPS-ICOPS (Albuquerque, NM) Conference Record paper 4P3 (June, 2007).

73. Pengvanich, P., Lau, Y. Y., Gilgenbach, R. M., Cruz, E., Luginsland, J. W., Schamiloglu, E., “Recent advances in magnetron phase locking, effects of frequency chirps and locking of multiple magnetrons”, PPPS-ICOPS (Albuquerque, NM) Conference Record, paper 5P17 (June, 2007).
74. Ragan-Kelley, B. and Verboncoeur, J.P., "Two-dimensional axisymmetric Child-Langmuir scaling law", 2008 IEEE IVEC, Monterey, CA USA (2008).
75. Ragan-Kelly, B. and Verboncoeur, J., "Two-dimensional Axisymmetric Child-Langmuir Scaling Law", Bull. Am. Phys. Soc. **52**, 292 (2007).
76. Roberto, M., Pessoa, R.S., Parada, S., Petraconi, G., Roberson, G., Verboncoeur, J., "Global model and particle-in-cell simulations of low-pressure oxygen discharges: comparisons with experimental data", Int. Conf. Comp. Phys., Ouro Preto, Brazil (2008) invited.
77. Sirigiri, J.R., Shapiro, M.A., Temkin, R.J., Petillo, J.J. “Non-uniform cathode emission studies of a MIG gun”, Marchewka, C.D., IEEE Conference Record - Abstracts. 2005 IEEE International Conference on Plasma Science - ICOPS 2005 (IEEE Cat No. 05CH37707), p 118, (2005).
78. Sule, N., Scharer, J., Booske, J.H., “Measurement and Analysis of Advanced Field Emission Cathodes” 2009 IEEE International Vacuum Electronics Conference, IVEC 2009, Poster Presentation, Poster session 1.
79. Sule, N., Scharer, J., Booske, J.H., “Measurement and Analysis of Cold Field Emission Cathodes” 36th IEEE International Conference on Plasma Science, ICOPS 2008, Oral Presentation, Session IO3D-1.
80. Sule, N., Scharer, J., Booske, J.H., Sengele, S., Vlahos, V., “Measurement and analysis of advanced cold field emitting cathodes, “IEEE International Vacuum Electronics Conference, Rome, Italy, April 28-30, (2009).
81. Sule, N., Scharer, J., Booske, J.H., Vlahos, V., Sengele, S., “Measurement and analysis of advanced field emission cold cathodes,” 36th IEEE International Conference on Plasma Science, San Diego, CA, May 31-June 5, (2009).
82. Tang, W.; Lau. Y.Y., “A higher dimensional theory of electrical contact resistance”, in Conference Abstract of 2008 IEEE International Vacuum Electronics Conference (Monterey, CA) , p. 212 (2008).
83. Tang, W.; Gomez, M.R.; French, D.M.; Zier, J.C.; Zhang, P.; Lau, Y.Y., Gilgenbach, R.M., “HIGHER DIMENSIONAL THEORY OF CONTACT RESISTANCE AND EXPERIMENTAL VALIDATION,” Bull. Am. Phys. Soc. **54**, No. 15, p. 206 (2009).
84. Taverniers, S., Lim, C. -H., and Verboncoeur, J.P., "2d particle-in-cell modeling of dielectric insulator breakdown", 36th IEEE ICOPS, San Diego, CA (2009).
85. Verboncoeur, J. P. and Nam, S. K. "An Enhanced Global Model for High Pressure Microwave-Driven Gaseous Breakdown", 19th Int. Symp. Plasma Chem., Bochum, Germany (2009).
86. Verboncoeur, J. P., "Computer Experimentation: Particle-in-Cell Simulation of Collisional Plasmas", 19th Int. Symp. Plasma Chem., Bochum, Germany (2009) invited.
87. Verboncoeur, J. P., Kim, H.C., Wang, Y., and Lau, Y.Y., "Transition of Dielectric Window Breakdown from Vacuum Multipactor to Collisional Microwave Discharge: a General Scaling Law", 34th IEEE ICOPS, Albuquerque, NM (2007) invited.

88. Verboncoeur, J. P., Nam, S.K., "Microwave dielectric window breakdown: from vacuum multipactor to collisional discharge", Int. Conf. Comp. Phys., Ouro Preto, Brazil (2008) invited.
89. Verboncoeur, J. P., Nam, S.K., and Lau, Y.Y., "Advances in modeling microwave window breakdown", 35th IEEE ICOPS, Karlsruhe, Germany (2008), invited.
90. Verboncoeur, J.P., "Particle simulation of plasmas: review and advances", *12th International Congress on Plasma Physics*, 25-29OCT, Nice, France (2004). Invited.
91. Verboncoeur, J.P., Cartwright, K.L., and Murphy, T., "Space-charge limited emission models for particle simulation", *30th IEEE ICOPS*, Baltimore, MD (2004).
92. Verboncoeur, J.P., Cartwright, K.L., and Murphy, T., "Space-charge limited emission models for particle simulation", *Bulletin American Physical Society* **49** (2004).
93. Verboncoeur, J.P., Feng, Y., Cartwright, K., and Murphy, T., "Space-Charge-Limited Emission Models for Particle Simulation", Bull. Am. Phys. Soc. 49, 186 (2004).
94. Verboncoeur, J.P., Kim, H.C., Chen, Y., and Lau, Y.Y., "Modeling RF window breakdown: from vacuum multipactor to volumetric ionization discharge", *27th IEEE International Power Modulator Symposium*, Washington, D.C. USA (2006), invited.
95. Verboncoeur, J.P., Nguyen, C., Lim, C.H., and Hammel, J., "A Boltzmann-PIC-MCC hybrid model for collisional transport in the tokamak divertor sheath", SIAM Comput. Sci. Engr., Costa Mesa, CA (2007).
96. Vlahos, V., Booske, J. H., Morgan, D.,"Material analysis and characterization of cesium iodide (CsI) coated C fibers for field emission applications, "IEEE International Conference on Plasma Science, Karlsruhe, GE, June 15-19 (2008).
97. Vlahos, V., Holby, E.F., Berta, A.K., Morgan, D.D., and Booske, J.H., "Work Function of Cathode Emitter Materials Obtained by Ab-Initio Quantum Mechanical Modeling," IEEE International Vacuum Electronics Conference and IEEE International Vacuum Electron Sources Conference, IVEC/IVESC 2006, Monterey, CA , 25-27 April, (2006). **Finalist selection for Best Student Paper Award.**
98. Vlahos, V., Miller, R., Morgan, D., Booske, J.H., Limbach, S., Jacobs, J., Sengele, S., and Lau, Y.Y., "Characterization of Material Performance of Carbon-Based Field Emitters," International Conference on Plasma Science, 4-8 June, Traverse City, MI, (2006).
99. Vlahos, V., Miller, R., Morgan, D., Booske, J.H., Limbach, S., Jacobs, J., Sengele, S., and Lau, Y.Y., "Characterization of Material Performance of Carbon-Based Field Emitters," International Conference on Plasma Science, 4-8 June, Traverse City, MI, (2006).
100. Vlahos, V., Morgan, D., Booske, J. H., Turek, L., Kirshner, M., Kowalczyk, R., and Wilsen, C., "An ab-initio Molecular Dynamics Model of the Scandate Cathode," IEEE International Vacuum Electronics Conference, Monterey, CA, April 22-24 (2008). **Best Student Paper Award**
101. Vlahos, V., Morgan, D., Booske, J.H., "Ab initio modeling of Ba-O-Sc on W cathode materials," Materials Science and Technology 2009 Conference, Symposium on Discovery and Optimization of Materials through Computational Design, Pittsburgh, PA, Oct. 25-29, (2009).
102. Vlahos, V., Morgan, D., Booske, J.H., Shiffler, D., "Surface and bulk characteristics of cesium iodide (CsI) coated carbon (C) fibers for high power microwave (HPM) field emission cathodes," 50th Annual Meeting of the American

Physical Society's Division of Plasma Physics, paper TO3-5, Dallas, TX, Nov. 17-21 (2008).

103. Vlahos, V., Morgan, D., Booske, J.H., Shiffler, D., "Surface chemical analysis of cesium-iodide (CsI) coated carbon (C) fibers and thin films for field emission applications," IEEE International Vacuum Electronics Conference, Rome, Italy, April 28-30, (2009).

104. Vlahos, V., Morgan, D.D., and Booske, J.H., "New Insights in the Modification of the Work Function of Cathode Materials due to Thin Surface Coatings using *Ab-initio* Modelling," IEEE International Vacuum Electronics Conference, May 15-17, Kitakyushu, Fukuoka, Japan (2007).

105. Wang, Y. and Verboncoeur, J.P., "Non-harmonic behavior induced by the particle-in-cell (PIC) scheme for cold plasma oscillations", 36th IEEE ICOPS, San Diego, CA (2009).

106. Zhang, Peng; Lau, Y.Y.; Gilgenbach, R.M., "RF POWER LOSS AND ELECTRIC AND MAGNETIC FIELD ENHANCMENTS DUE TO SURFACE ROUGHNESS," 2009 IEEE International Vacuum Electronics Conference (Rome, Italy), p. 556 (1009).

6. Honors and Awards

6.1. Co-PI's

John Verboncoeur:
During this grant: IEEE Senior Fellow; promoted to Full Professor in Residence; Air Force IPA at Kirtland AFB

Richard Temkin:
Lifetime: Robert L. Woods Award of Dept. of Defense for Vacuum Electronics (2000); Fellow, Institute of Physics (London) (1999); Certificate of Recognition, IEEE Electron Device Society (1998); Kenneth J. Button Prize and Medal, The Institute of Physics, London (1995); Certificate of Merit, U. S. Dept. of Energy and ITER Program (1995); Fellow, IEEE (1994); Fellow, American Physical Society (1992); IBM Postdoctoral Fellow, Harvard University (1972 – 1974)

J.H. Booske:
During this Grant: Fellow of the IEEE (2007); Named to hold the Duane H. and Dorothy M. Bluemke Professorship of Engineering (2007); Appointed Chair of Electrical and Computer Engineering Department, University of Wisconsin-Madison (2009).
Lifetime: University of Wisconsin Vilas Associate Award (2004 – 2006) for research excellence, U.S. National Science Foundation Presidential Young Investigator Award (1990-1997); University of Wisconsin Chancellor's Distinguished Teaching Award (1995), Benjamin Smith Reynolds Award for Excellence in Teaching Engineering (2000).

R.M. Gilgenbach:
Lifetime: Fellow of the IEEE (2004), PSAC Award from IEEE (1997), Fellow of the American Physical Society Division of Plasma Physics (1996), Invited Nominator for Nobel Prize in Physics

Y.Y. Lau:
During this Grant: Fellow of IEEE (2007)
Lifetime: PSAC Award from IEEE (1999), Fellow of the American Physical Society Division of Plasma Physics (1986), Xi Scientific Society Applied Science Award (1989), Invited Nominator for Nobel Prize in Physics

Andreas Neuber:
During this grant: Promoted to Full Professor; Whitacre Research Award 2008, COE, Texas Tech University; Outstanding Researcher, 2009, College of Engineering, Texas Tech University;

James Dickens:
During this grant: Promoted to Full Professor

6.2. Additional Recognition of the Sponsored Research and Personnel

6.2.1. Invited or Award-winning Talks

1. Booske, J.H., He, X., Miller, R.L., Morgan, D., Scharer, J.E., Vlahos, V., Gilgenbach, R.M., Jordan, N.M., Lau, Y.Y., Feng, Y., Verboncoeur, J. "Innovations and fundamental insights of advanced field emission cathodes for high power microwave (HPM) sources,**"**, **Invited Talk**, IEEE Pulse Power and Plasma Science Conference, June 17-22, Albuquerque, NM (2007).
2. Booske, J.H., "Innovations and fundamental insights of advanced field emission cathodes for high power microwave sources," **invited tutorial lecture**, International Vacuum Nanoelectronics Conference, Chicago, IL, July 8-12 (2007).
3. Booske, J.H., "Plasma Physics Challenges of MMWave-to-THz and High Power Microwave Generation," **Invited Plenary Review Talk**, 49th Annual Meeting, American Physical Society's Division of Plasma Physics, November 12-16, (2007).
4. Hidaka, Y., Observations of Regular Filamentary Plasma Arrays in High-Pressure Gas Breakdown by 1.5 MW, 110 GHz Gyrotron Pulses, , APS Div. Plasma Physics, Dallas, TX, Nov., (2008). **Invited (Abstract)**.
5. Hidaka, Y.; Choi, E.M.; Mastovsky, I.; Shapiro, M.A.; Sirigiri, J.R.; Temkin, R.J.; Edmiston, G.F.; Neuber, A.A.; Oda, Y. "Plasma structures observed in gas breakdown using a 1.5 MW, 110 GHz pulsed gyrotron," Physics of Plasmas, v 16, n 5, p 055702 (7 pp.),a figure from this article was featured on the cover of the May issue of the journal, May (2009) Invited.
6. Kim, H.C., Verboncoeur, J.P., Edmiston, G.F., Neuber, A.A., Lau, Y.Y. and Gilgenbach, R.M., "Transition of window breakdown from the vacuum multipactor discharge to the collision rf plasma", *7th IEEE International Vacuum Electronics Conference*, Monterey, CA USA (2006), **keynote**.
7. Kim, H.C. and Verboncoeur, J.P., "Physics of a single-surface multipactor discharge," *Conference on Computational Physics*, Gyeongju Korea (2006), **invited**.
8. Kim, H.C. and Verboncoeur, J.P., "Modeling of RF Window Breakdown," *International Conference on Computational Physics*, Gyeongju Korea (2006), **invited.**
9. Krile, J., Neuber, A., Edmiston, G., Dickens, J., "Surface Flashover under RF and Unipolar Excitation at Atmospheric Conditions", presented at the 27th Power Modulator Symposium and 2006 High Voltage Workshop, Washington, DC, May 14-18, (2006) **invited.**
10. Krile, J. T., Neuber, A. A., Krompholz, H. G., "Effects of UV Illumination on Surface Flashover under Pulsed Unipolar Excitation," presented at the 2007 IEEE Pulsed Power and Plasma Science Conference, Albuquerque, NM June 17-22, (2007)**invited.**
11. Morales, K., Krile, J., Neuber, A., Dickens, J., Krompholz, H., "Pulsed Unipolar Surface Flashover At Atmospheric Conditions", presented at the 27th Power Modulator Symposium and 2006 High Voltage Workshop Washington, DC. May 14-18, (2006) **invited.**

12. Neuber, A.,“Dielectric Surface Flashover at Atmospheric Conditions under High Power Microwave Excitation,” 2006 48th Annual Meeting of the Division of Plasma Physics,Meeting Id: DPP06, Philadelphia, PA,October 30-November 3,(2006)**invited.**
13. Neuber, A., Krompholz, H., Dickens, J., Kristiansen, M., “Dielectric Surface Flashover Research at Texas Tech University,” to be presented at the 1st Euro-Asian Pulsed Power Conference, Chengdu, China ,Sept. 18 -22, (2006) **invited.**
14. Neuber, A., “Dielectric Surface Flashover under Pulsed Unipolar and RF Excitation,” presented at the DPG Frühjahrstagung des AMOP, Düsseldorf, March 19-23, (2007), Germany **(invited plenary presentation)**
15. Roberto, M., Pessoa, R.S., Parada, S., Petraconi, G., Roberson, G., Verboncoeur, J., "Global model and particle-in-cell simulations of low-pressure oxygen discharges: comparisons with experimental data", Int. Conf. Comp. Phys., Ouro Preto, Brazil (2008) **invited**.
16. Verboncoeur, J.P., “Particle simulation of plasmas: review and advances”, *12th International Congress on Plasma Physics*, 25-29OCT, Nice, France (2004). **Invited**.
17. Verboncoeur, J.P., Kim, H.C., Chen, Y., and Lau, Y.Y., “Modeling RF window breakdown: from vacuum multipactor to volumetric ionization discharge”, *27th IEEE International Power Modulator Symposium*, Washington, D.C. USA (2006), **invited**.
18. Verboncoeur, J. P., Kim, H.C., Wang, Y., and Lau, Y.Y., "Transition of Dielectric Window Breakdown from Vacuum Multipactor to Collisional Microwave Discharge: a General Scaling Law", 34th IEEE ICOPS, Albuquerque, NM (2007) **invited**
19. Verboncoeur, J. P.. Nam, S.K., and Lau, Y.Y., "Advances in modeling microwave window breakdown", 35th IEEE ICOPS, Karlsruhe, Germany (2008), **invited**.
20. Verboncoeur, J. P., Nam, S.K., "Microwave dielectric window breakdown: from vacuum multipactor to collisional discharge", Int. Conf. Comp. Phys., Ouro Preto, Brazil (2008) **invited**.
21. Verboncoeur, J. P., "Computer Experimentation: Particle-in-Cell Simulation of Collisional Plasmas", 19th Int. Symp. Plasma Chem., Bochum, Germany (2009) **invited**.
22. Verboncoeur, J. P., “Particle Simulation of Plasmas: Review and Advances, “ Kwangwoon University, S. Korea (2004) **invited.**
23. Verboncoeur, J. P., “Particle Simulation of Plasmas: Review and Advances,” Pusan University, S. Korea (2004) **invited.**
24. Verboncoeur, J. P., “PIC Modeling Review”, Kwangwoon University, S. Korea (2005), **invited.**
25. Verboncoeur, J. P., “Dielectric Multipactor”, Pohang Institute of Technology, S. Korea (2005) **invited.**
26. Verboncoeur, J. P., “PIC Modeling”, Paul Sabatier University, Toulouse France (2006) **invited.**
27. Verboncoeur, J. P., “Microwave Window Breakdown”, Center for Beam Physics, Lawrence Berkeley Laboratory (2006) **invited.**
28. Verboncoeur, J. P., “Particle Simulation of Plasmas: Review and Advances”, Texas Institute of Technology, Lubbock, Texas (2007) invited.
29. Verboncoeur, J. P., “Modeling and Simulation of Microwave Breakdown”, University of Innsbruck, Austria (2008) **invited.**

30. Verboncoeur, J. P., “Modeling Breakdown”, Lawrence Livermore National Laboratory (2008) **invited.**
31. Verboncoeur, J. P., “PIC Modeling Techniques”, Nuclear Physics Institute, Catania Italy (2009) **invited.**
32. Verboncoeur, J. P., “Using XOOPIC”, Nuclear Physics Institute, Catania Italy (2009) **invited.**
33. Vlahos, V., Holby, E.F., Berta, A.K., Morgan, D.D., and Booske, J.H., “Work Function of Cathode Emitter Materials Obtained by Ab-Initio Quantum Mechanical Modeling,” IEEE International Vacuum Electronics Conference and IEEE International Vacuum Electron Sources Conference, IVEC/IVESC 2006, 25-27 April, (Monterey, CA, 2006). **Finalist selection for Best Student Paper Award.**
34. Vlahos, Vasilios, Morgan, Dane, Booske, John H., Turek, Ladislav, Kirshner, Mark, Kowalczyk, Richard, and Wilsen, Craig, “An ab-initio Molecular Dynamics Model of the Scandate Cathode,” IEEE International Vacuum Electronics Conference, Monterey, CA, April 22-24 (2008). **Best Student Paper Award.**

6.2.2. Other recognitions

- Verboncoeur, John: invited instructor, Plasma Simulation Workshop 2007 (Ljubljana, Slovenia)
- Verboncoeur, John: invited instructor, Plasma Simulation Workshop 2008 (Tapei, Taiwan)
- Verboncoeur, John: invited instructor, Plasma Simulation Workshop 2009 (Innsbruck, Austria)
- Nam, Sang Ki at UC-Berkeley received Green Card based on importance of research to national security (took position at LLNL)
- AFOSR-supported UC-Berkeley PTSG code suite now exceeds 1000 users, with over 250 journal publications in the last decade